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The acoustic influence of the scenery on the audience sound perception: the case of the ancient theatre of Syracuse

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Summary
Known in the past for its spectacular acoustic characteristics, the ancient theatre keeps today an important role as a modern stage: during the summer season many important theatrical events are organized in the frame of its ancient ruins, keeping alive a tradition that attracts people all around the world. But, without doubts, the actual conditions for the audience are deeply changed, affected by "modern" noises and damaged situation of the theatre itself. The insertion of the scenery elements has also to be considered as a variable that can modify the sound propagation in the theatre, with better or maybe worst results.
In this article a research conducted on the acoustic perception of the audience of the Greek theatre of Syracuse is presented. A parametric study realized through a technical software (Odeon ® version 12.1) has been performed considering different scenery conditions, from the empty theatre and by adding different scenic elements to evaluate their influence on passive acoustics. In a first study, the three-dimensional model considered was built based on the scenery realized by OMA in 2012 for the *48th Edition of Classical Plays at Syracuse's Theatre*. Lately, the comparison between the condition with and without the scenery allowed establishing a few acoustic guidelines for the scenic design. The result of these first two studies was the proposition of scenic elements that allow the preservation and the improvement of the original acoustic apparatus.
In this work, the comparison through auralization of the different conditions of the theatre provides interesting suggestions on the way toward an efficient scenic design and aims at satisfying the audience acoustic needs and at a deeper fruition of the theatrical experience nowadays. In particular five different conditions were tested: I. Empty condition, II. OMA's scenery, III. A scenery based on the re-elaboration of the historical configuration, IV. A scenery developed for modern theatrical performances, V. Empty condition with loudspeakers.

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1. Introduction

The Syracuse theatre is an open-air theatre in the South of Italy intensively used for the cycle of classical representations organized every year by the Italian association INDA (Istituto Nazionale Dramma Antico) during the summer season. This event subjects the theatre area to substantial changes for almost four months per year: different temporary sceneries, usually conceived on the idea of the classical geometry, are inserted in the *orchestra* (stage area), while the *cavea*'s steps (where the audience sits) are covered by a

protection material – as wood. Previous research has investigated the positive acoustical effects of the insertion of specific sceneries in the Syracuse and other ancient theatres, through computer simulations and scale modelling, in ancient and modern times [1] [2], referring principally to the objective room criteria defined in [3].
Starting from a similar investigation [4] [5], the authors of this paper propose a further analysis based on listening tests, in order to quantify the sound experience of the audience inside the theatre. The virtual simulation has been chosen as an instrument to explore the different possibilities of acoustic propagation, through the technique of auralization. It is based on capturing or modelling a binaural impulse response, which is then convolved with anechoic music, speech or other suitable signals, giving a realistic effect of sound diffusion in the theatrical space.
Some previous experiences on the virtual reconstruction of sounds in ancient theatres have been introduced by the European Project ERATO [6]. But in this case the purpose was purely educational: recorded in anechoic environment, three pieces of music in the antic style have been used in animated virtual scenarios, including sounds from the audience. The present research focuses instead in exploring the differences between alternative scenic conditions, referring to the types of performances realized today in ancient theatres.
In this paper we report the results of a study on three reference soundtracks (*speech*, *drums* and *orchestra*), applied with a common listening test method. The task requested to the listeners was to express a preference respect two tracks, each one obtained with auralizations from virtual models of the theatre. In total, five different conditions have been compared: in absence of scenery, with a Public Address (P.A.) System and with three different types of scenery. A statistical analysis has been then conducted on the results, in order to define a score for the sceneries and the possible correlations between them.
The target of this research is a better comprehension of the sound perception by the audience and its preferences from an acoustic point of view, in order to define a most appropriate way of modern usage of ancient theatres, based on two principles:
- Respect of the original function and acoustical apparatus;
- Pondered integration of modern technologies in historical spaces.

2. The Ancient Theatre of Syracuse

Figure 1. The theatre of Syracuse, empty condition

The ancient theatre of Syracuse (Fig. 1) dates from the fifth century B.C.; the structure as it appears today is similar to the Roman type, though the theatre was conceived in the Greek period, changing over time. The part that survived until today shows the *cavea* with a diameter of 143 m: it extends radially around the *orchestra*, a plane semi-circle of 29 m diameter located in front of the stage (or *scena*) that is not anymore preserved. It is possible to subdivide the *cavea* in three zones: *ima*, *media* and *summa*. Each part is divided from the other by a specific boundary element: starting from the *orchestra*, the *ima cavea* corresponds to the first twelve steps and it has a slope of 22.5°; after a higher step of 0.86 m, it becomes *media cavea* and the inclination changes in 20.8°; a large passage, called *diàzoma*, bounds this part and suddenly the summa *cavea* begins, keeping the same average slope.
A schematic representation of the empty theatre is shown in Figure 2a. Then Figures 2b, 2c and 2d are referred to the sceneries analysed in this articles, presented in the following descriptions.

2.1. The OMA scenery for the 48th Edition of Classical Plays at Syracuse's Theatre

The scenery was realized in 2012 by the architectural studio OMA and it is composed by three elements: the first one is the *ring*, a suspended walkway at the level of the *diàzoma*, that complete the semi-circle of the *cavea*; the second is the *machine*, an inclined circular platform, 7 m high, mirroring the amphitheater; the third is the *raft*, a circular stage that reimagines the *orchestra* space. The materials used to build the three elements of the scenery are steel for the structures and wood as coverture. Any

preliminary acoustical investigation has been realized during the project.

2.2. The sceneries proposed by the authors

In a previous study presented in [5], three generic scenic elements, inspired to the classical geometry of the ancient theatre of Syracuse described in [1], have been analyzed from the acoustic point of view through the help of virtual simulations:

- Scenic Front (corresponding to the ancient *Scaenae Frons*);
- Stage Floor (*Orchestra*);
- Back Panels (*Porticus*).

Analyzed different types of geometrical configuration for these elements, good acoustic results have been achieved with a Scenic Front designed as vertical wall 10 x 4 m^2, located behind the *orchestra* at level of *scaenotecae* (30 m from the first row of the *cavea*). The Back Panels have been located as bottom closure of the surviving *cavea*, as vertical panels, with dimensions 4 x 2 m^2. The Stage Floor is a round pavement covering the area of the *orchestra*. The chosen material for the three elements has been a general reflective wood, $\alpha_{0.5\text{-}2kHz}$ equal to 0.05. Then it has been characterized with two scattering coefficients: 0.1 (i.e. reflection mostly specular) for the Stage Floor and 0.7 (reflection mostly diffuse) for the Back Panels. The Scene Front, 15 m high, has been divided at midpoint and 0.1 has been assigned to the lower part (to enhance the actor voice in the *orchestra*) and 0.7 to the upper part (to diffuse it in the rest of the *cavea*).

1.2.1. Echo detection

Referring to [7], the presence of an echo at some audience positions has been confirmed as typical in ancient theatres, due to the semicircular shape of the *cavea* itself and to the introduction of sound reflective materials with the sceneries.

Two sources in different positions were tested using the *Echo Criterion* (EC) suggested by Dietsch & Kraak for speech and orchestral music [8]: with an omnidirectional source (corresponding e.g. to an orchestra) located at the center of the *orchestra*, it has been verified that echo leads to a disturbance with and without Back Panels in almost all the *cavea*, with some improvements in the lower part for higher frequencies (4000 Hz); with a directional source (e.g. the voice of an actor) shifted of 1 m from the Scenic Front, echo is not so relevant, except for few positions in the upper *cavea* in presence of the Back Panels, at lower frequencies. For this reason, the sceneries proposed by the authors are two:

- Guidelines 1: Scenery composed by three elements (Scenic Front, Stage Floor, Back Panels) respecting the historical scenic conformation;
- Guidelines 2: Scenery composed by two elements (Scenic Front, Stage Floor), for modern performances as dramas and comedies (speech).

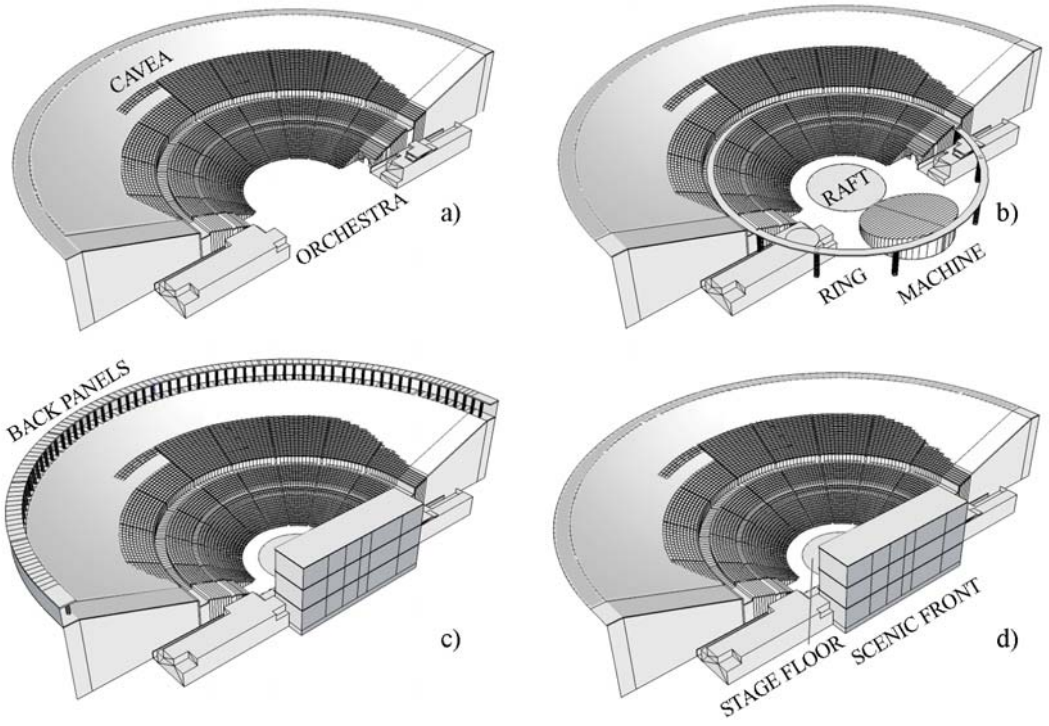

Figure 2. Theatre conditions analyzed: a) Empty; b) OMA scenery; c) Guidelines scenery 1 (Historical); d) Guidelines scenery 2 (Speech)

2.3. The P.A. system

In the last years a P.A. system has been introduced inside the theatre to support and enhance the acoustic of the building. The loudspeakers and subwoofers actually in use have been disposed in the virtual model as represented in Figure 3. For the analysis, the model with loudspeakers was empty, without considering the presence of additional scenery.

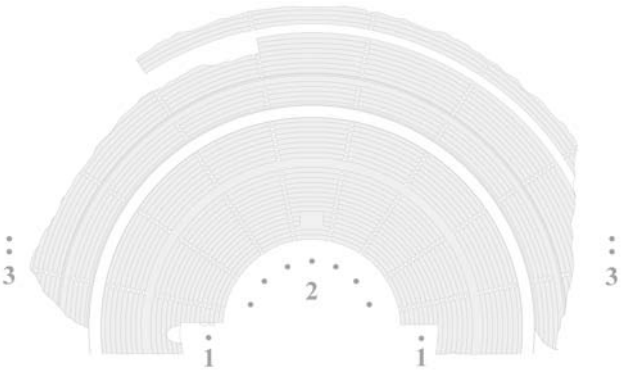

Figure 3. Disposition in plan of loudspeakers and subwoofers simulated:

1. *Scaenotecae* area (*orchestra*): 4 Loudspeakers Yamaha Pro Audio IH2000-64, 2 Subwoofers Yamaha Pro Audio IL1115

2. *Ring* area (*orchestra*): 7 Loudspeakers Yamaha Pro Audio IH2000-95

3. Scenic Towers area (upper *cavea*): 2 Arrays Worx Audio M80i, 2 Subwoofers Yamaha Pro Audio IL1115

3. Preliminary acoustical analysis

The described five virtual models (the four of Figure 2 plus the empty theatre with the P.A. system) have been inserted and simulated in Odeon ® version 12.1, an acoustic software based on a hybrid calculation that combines the Image Source Method and the Ray-Tracing Method.
To conduct a preliminary analysis, in each model 57 receivers were distributed on the five main axes of the *cavea* (central, diagonal and lateral), starting from the centre of the *orchestra*, where an omnidirectional source was located (S2 in Fig. 5). The models were virtually calibrated on the basis of a previous measures campaign conducted on the empty theatre and described more in detail in [5].
The goal of this part of the research was to compare the five different conditions from the acoustical point of view, using the room criteria defined in [3]. The parameter taken as principal reference is the *Sound Strength* (G): indeed, as demonstrated already in [4] and confirmed by an analogous study conducted on Chinese unroofed theatres [9], the *Reverberation Time* (RT) does not give reliable results to describe the impulse response in open-air theatres. Therefore, the positional dependence of G in the theatre, shown as logarithmic regression curves for the sake of easier comparison, is depicted in Figure 4.

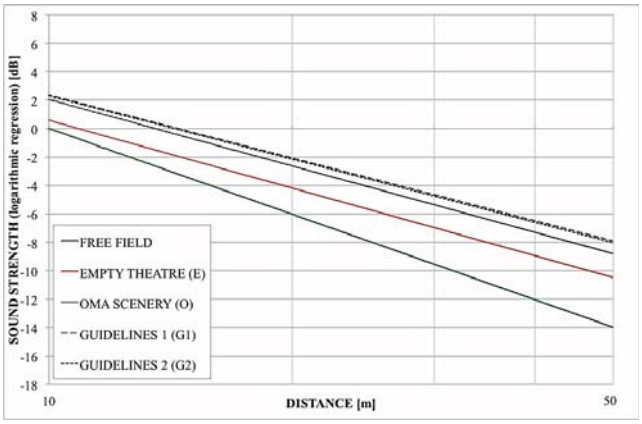

Figure 4. Simulated $G_{0.5\text{-}2kHz}$ logarithmic regression curves for impulse responses obtained in free field, in empty theatre, with OMA scenery, with Guidelines 1 and Guidelines 2.

All data simulated for middle frequencies ($G_{0.5\text{-}2kHz}$), for each source-receiver combination, were considered. For distances below 10 m from the modelled source, the decay of the G with distance follows quite well the $1 / r^2$ behaviour around an omnidirectional source in free field. Afterwards the consequences of introduction and changes of the scenery start to be remarkable.
In fact the simulations have shown that the effect of adding sceneries on the G-values was more than the *Just Noticeable Difference* (JND) of 1 dB as stated in [3]. At the furthest positions there is a gain of almost 3 dB compared to the empty theatre condition; as expected, better results are obtained for the sceneries conceived with acoustical intents, whose benefits are comparable to those obtained with a P.A. system inserted in the empty theatre.
However, from this preliminary analysis is not possible to establish a ranking of best acoustic performance between the five conditions analysed, neither to support the possibility of substitution of the P.A. system actually in use with one of the proposed scenery. Listening tests, object of this research, are conducted to determine the best acoustical conditions, because the simple analysis of objective parameters is not sufficient.

4. Listening Test Methodology

To identify the perceptual differences between the different conditions a listening test was carried out on the auralized soundtracks prepared with Odeon ® version 12.1. Unfortunately, there is no recommended methodology to evaluate auralizations: therefore, methods similar to the ones for assessment of audio codecs have been used. One good comparison method is ABX paradigm, in its normalized version referring to [10], then specified in [11] with standardized interval scales.

4.1. Auralized soundtracks

For this study five sets were experimented:

- *E* - Empty
- *G1* - Guidelines 1 - with Back Panels
- *G2* - Guidelines 2 - without Back Panels
- *OMA* - scenery
- *EA* - Empty Amplified

The tests have been prepared with three stimuli: *speech*, *drums* and *orchestra*.
All the auralizations refer to a unique listening position R in the theatre, shown in Figure 5.

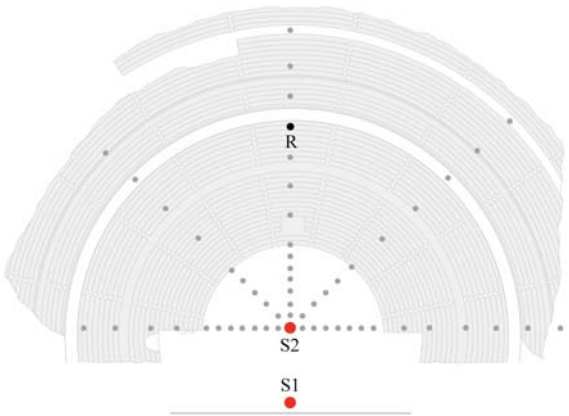

Figure 5. Disposition in plan of sources (red), receivers (grey) and chosen listening position (black)

The sound source S1 for *Speech* Listening Test (Raised human voice directional file, Sound Power of 78 dB) has been located symmetrically at 1 m from Guidelines sceneries position (indicated as a line in Fig. 5); S2 for *Drums* (Omnidirectional, 80 dB) and for *Orchestra* (Omnidirectional, 100 dB) was placed in the middle of the stage. The tracks were recorded in anechoic room and then virtually convolved, with duration of 6-7 seconds for each signal. The levels perceived for each auralization were set up keeping the acoustic differences between the scenic configurations; only for the amplified condition the gain was reduced of 10 dB to obtain a comfortable reproduction level.

4.2. Test organization

The listening tests have been conducted using a survey defined by the authors, whose graphical user interface is depicted in Figure 6.
The five sets have been compared between them two by two, for a total of 10 pairs: to the listeners, they appeared as a generic comparison between tracks “A” and “B”. The task requested was to rate them on the base of [11]: to check a possible bias, each pair has been repeated, switching the order of the two samples; at the end, the whole test set contained 20 pairs, with an overall duration of 15-20 min per test for each listener. About 16-17 subjects for stimulus were chosen on the basis of a pre-screening procedure: an audiometric test has been performed and each participant reported normal hearing. Since the strict timing, it has not been possible to select them also on previous experiences in acoustic tasks: some of them were at their first experiment.

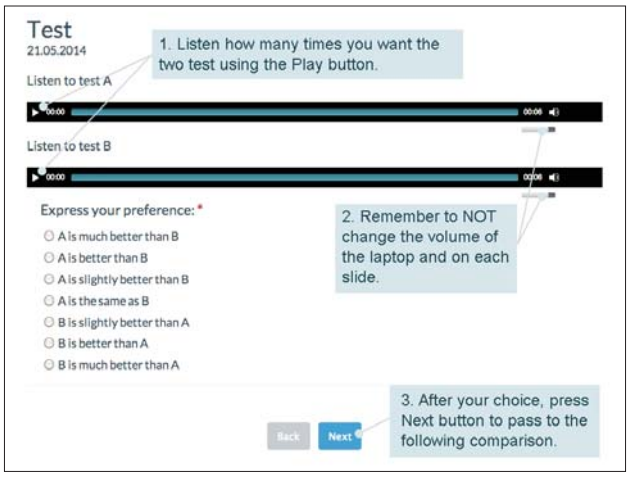

Figure 6. The graphical user interface utilized in the tests, with the information for the listeners to proceed; grading scale from reference [11].

The listening tests have been realized in three days (one for each stimuli), in a quiet office in Polytechnic of Turin. The surrounding conditions were the same for all the listeners: they wore professional headphones (Sennheiser HD 600) and used the same laptop (with sound card TASCAM US-144). The reproduction level should have been around 60 – 72 dB as suggested in [12]. The Background Noise Level in the office, registered with a sound level meter (XL2 Handheld Audio and Acoustic Analyser produced by NTi Audio),

was 28.8 dB(A). The subjects were aware that the task was to compare two soundtracks and to answer to all the questions, rating the samples according to their preferences, but not about which was the correspondence between soundtracks and relative theatre scenic condition.

4.3. Statistical Analysis

In this research a post-screening statistical analysis has been conducted to assess the ability of the listeners to make correct identifications, and thus the reliability of the answers given by a listener. The post-screening on the ability of the listeners to make correct identifications has been realized counting how many times the answer given by the same subject on the same repeated pair *A + B* was respected and determining 95% confidence intervals, as seen in [13]. With the post-screening, listeners that showed reliability far better or worse than average were excluded from further analyses.

5. Results

The purpose of the experiment was to establish a ranking of preference between different acoustical conditions obtained with spatial variations of the sceneries inside the theatre, including also the conditions of empty theatre with and without amplification. It has been noticed that some results are similar to those obtained from a survey conducted by the authors directly on the audience of the theatre of Syracuse; this survey, realised to investigate the acoustic perceptions of the spectators during the performances, has been distributed in form of questionnaires in occasion of the last edition of classical plays organized by INDA (2014), for a total of 42 interviewees. Thus some of the main findings will be analysed also taking into consideration this further comparison.

5.1. Listening Test 1 – Speech

The stimulus consisted in a sentence read by an actress. Seventeen listeners have been selected at the beginning, reduced to 15 with the post-screening operation (ANOVA). The results of Test 1 are shown in Figures 7a and 7b: the graphs present the average values referred to the answers scores (-3; +3) on the vertical axis, with upper and lower limits reported on the corresponding 95% uncertainty bars. On the horizontal axis of Figure 7a the pairs of the samples compared are presented, then repeated and inverted in Figure 7b (e.g. *E + G1* and *G1 + E*, previously both presented to the listener generally as *A + B*).

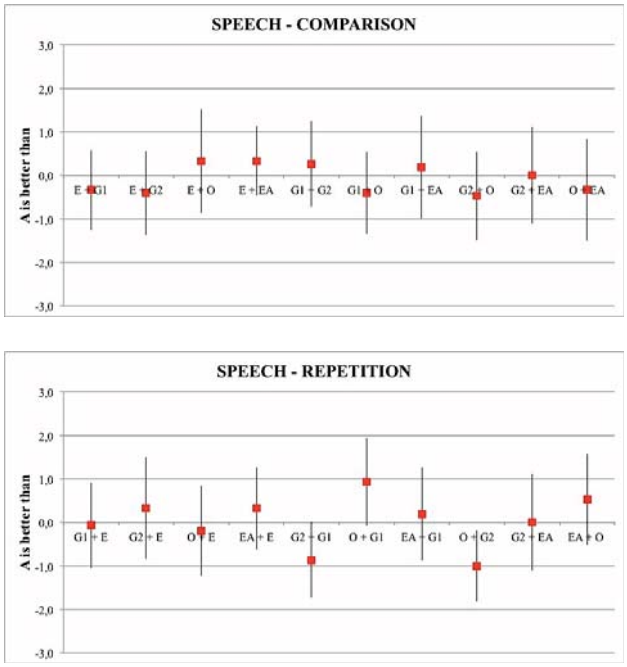

Figure 7. Results of the Listening Test 1 with *Speech* stimulus for all the seelected listeners (15); 10 couples compared (a), then repeated and inverted (b). If positive, answer "A" has been preferred, if negative answer "B".

For corresponding couples, the reliability of the answers is confirmed when the results are opposite. As clearly visible from the confrontation of the two graphs, the following couples do not present conformity in the answers: *E + G1*, *E + EA*, *G1 + EA* and *G2 + O*. Therefore, both the empty condition with and without loudspeakers (*E* and *EA*) seems to be not always easily judged. Otherwise, trying to establish a ranking between the other samples, it is possible to notice that configurations with more sound amplification are preferred, as *G2* respect *E*, *G1* respect *G2*, *EA* respect *O*. This is in partial conformity with the G calculation done in the preliminary acoustical analysis: *G1* and *G2* are the theatrical configurations that have most sound diffusion. Furthermore, the comparison *O + G1* represents an unexpected result, with a marked preference for the acoustical condition determined by the OMA scenery that has been conceived without acoustical intents. Based on the expressed preferences, Listening Test 1 indicates that the listeners, even if not completely agreeing, slightly preferred the amplified voice in case of an actor speaking in the theatre, as reported in the final resume of the results (Table I). The uncertainty expressed is quite in conformity with the responses given by the people interviewed in Syracuse: the 34% of them agrees that the use of the P.A. System

reduces the acoustical conditions of the theatre, while the 37% asserts there is an improvement; the remaining 29% gave uncertain answers.

5.2. Listening Test 2 – Drums

The choice of the second stimulus depended on the diffused idea that percussions are the most ancient type of music; moreover, they are often used also for modern plays. Sixteen listeners participated to the listening test, and then only 14 have been selected after post-screening. The results for Test 2 are depicted in Figures 8a and 8b; again it is possible to identify easily the not reliable couples: *E + G1*, *E + O*, *E + EA*, *G2 + EA* and *O + EA*. It is again noticeable the necessity of more effort by the subjects in judging the conditions *E* and *EA*; this last one seems to be not anymore appreciated as in Test 1. It is also shown that a less reverberant condition is preferred, as demonstrated by *G2*, the scenic configuration collecting the highest number of preferences (*G2* respect *E*, *G2* respect *G1*, *G2* respect *O*). This is quite reasonable in the supposition that drum music has totally different acoustic requirements from those for orchestral music: indeed, in this other case long echoes are not typically a problem and that long reverberation time adds beauty and blend to the different instruments and harmonies; drum music needs instead more clarity, with fast attacks, and it is very sensitive to echoes.

On the basis of the conclusions of the previous Test, a further analysis on musical performances is conducted in Test 3.

5.3. Listening Test 3 – Orchestra

The last stimulus chosen is a classic music piece; indeed, one of the intent of this research is also to evaluate the possibilities of execution of other kinds of performance, besides the theatrical one. In this case, from 16 people that participated at the beginning, 15 have been considered. Figures 9a and 9b show the results obtained from Listening Test 3: couples *E + G1*, *E + O*, *G1 + O*, *G2 + O* *G2 + EA* and *O + EA* gave unreliable results, pointing out immediately a specific bias linked to configuration *O*. Comparing these results with those obtained with Test 2, it is possible to notice a similar trend of the answers; indeed there are also some correspondences for the uncertain couples. The two Listening Tests on music gave similar results: also in this case configuration *G2* is preferred to *G1* as scenic configuration. Unexpectedly, the reverberation is perceived as annoying also in orchestral music performances, while it has been not revealed the same behavior in Listening Test 1 (*G1* is preferred to *G2*). A parallel result emerges from the survey conducted directly in Syracuse: asking which are the more evident acoustic deficiencies present in the theatre, the majority of the interviewees did not notice the problem of the echo during the plays.

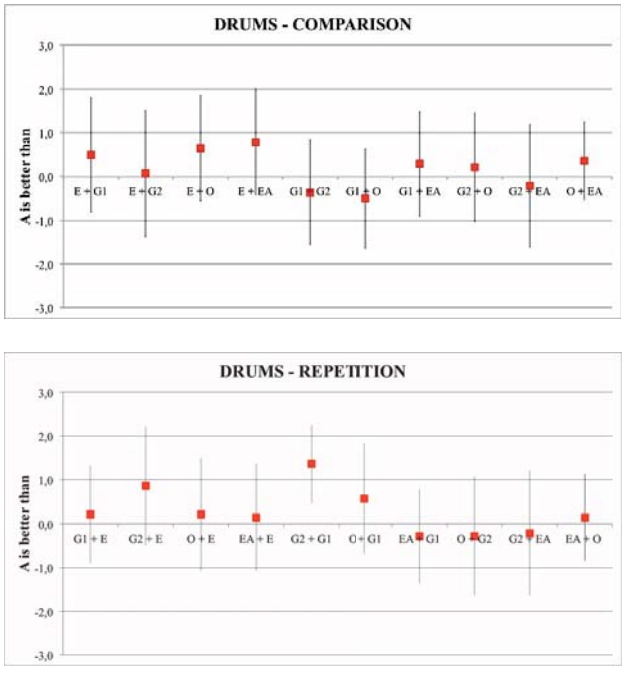

Figure 8. Results of the Listening Test 2 with *Drums* stimulus for all the selected listeners (14); 10 couples compared (a), then repeated and inverted (b).

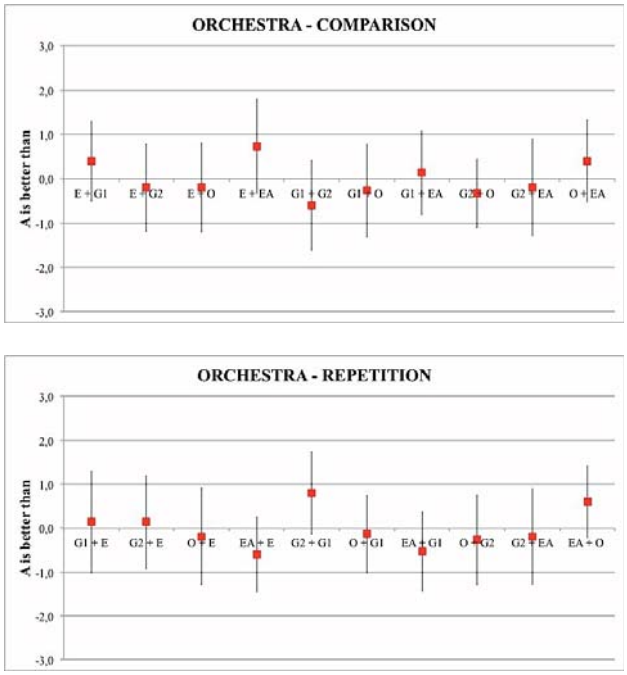

Figure 9. Results of the Listening Test 3 with *Orchestra* stimulus for all the selected listeners (15); 10 couples compared (a), then repeated and inverted (b).

6. Conclusions

This study provided data related to the acoustic perception of the audience inside the ancient theatre of Syracuse, referring to three consequential moments of research: I. a preliminary acoustical analysis on virtual models, II. the organization of subjective listening tests in laboratory, III. a survey conducted directly on the real audience of the theatre. The main results are summarized as follows, with a hypothesized classification of the sceneries resumed in Table I and obtained referring only to the certain couples (the more uncertain cases area marked with *):

1. In Listening Test 1 (*Speech*) the subjects indicated a slight preference for the amplified acoustic condition, with many uncertainties; this is also confirmed by the survey conducted directly in Syracuse. It is anyway evident a propensity respect the scenic configurations that enhance the propagation of the sound in the theatre and guarantee its reinforcement.
2. In Listening Test 2 (*Drums*) the task has been not always easily served out; accordingly to the listeners, they found many difficulties to answer. In this case the amplification has not been appreciated, but Guidelines 2 (without Back Panels) allowed ameliorating the propagation and the perception of the sound.
3. Listening Test 3 (*Orchestra*) confirmed the subjects' behaviour for music listening: G2 is the theatrical conformation that reached the highest number of preferences. The use of Back Panels to reflect the sound inside the *cavea* has not been appreciated for musical performance, although in ancient period a bottom closure (*porticus*) was previewed to obtain a more enclosed and reverberant space.
4. In general, more expert listeners and a training phase at the beginning of the listening tests (in order to accustom the subject to the grading scales) should allow solving some detected problems. In fact, the uncertainties on the averages (U_m) calculated by basing on the experimental values are rarely lower than 1. Sometimes, it is hard to discriminate among the results in order to create a ranking.
5. Therefore this research should be continued involving more subjects, to obtain even more reliable results, and analysing also other listener positions (diagonally, laterally, in the *orchestra* area), to define the acoustic perception of the rest of the audience.

Table I. Hypothesized classification

Ranking	*Speech*	*Drums*	*Orchestra*
1°	EA	G2	G2
2°	O*	O*	E*
3°	G1	E*	O
4°	G2	G1	G1
5°	E*	EA	EA

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